Fermi National Accelerator Laboratory

FERMILAB-TM-1864

PA1317 (L13): A Linac BPM Calibration Program

Elliott McCrory

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

November 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Fermilab

Technical Memo, TM-1864

Elliott McCrory
AD/Linac, MS 307, x4808
November 4, 1993

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I. Introduction

The purpose of this program is to determine the centers of the high-energy linac (HEL) BPMs using beam information, and to compare this information with the existing surveying information. It measures directly and quantitatively the amount of quad steering in each of the HEL quads. It is hoped that this program is all that is needed to make this measurement.

This procedure is based on the observation of the beam position in a BPM downstream of a quad while changing the magnetic field in that quad. If the beam is centered in the quad, then this change will have no effect on the trajectory of the beam. However, if the beam is off center at the quad, changing the field will steer the beam. This measurement therefore can be used to measure the position of the beam in the quad under examination.

II. Theory

Referring to Figure 1 on the next page, the standard matrix equation which describes the transverse properties of the beam in this region is:

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{final} = \mathcal{M}_{drift}\,\mathcal{M}_{quad}\begin{pmatrix} x \\ x' \end{pmatrix}_{init}$$

Expanding this equation to determine x_{final}, the following relation is obtained:

$$x_{final} = x_{init}\left(\cos\zeta - \sqrt{K}\,D\,\sin\zeta\right) + x'_{init}\left(\frac{1}{\sqrt{K}}\sin\zeta + D\cos\zeta\right)$$

$$\zeta = +KL,\ K = 0.2998\,g/p\,[\mathrm{Tm}^{-1}/(\mathrm{GeV/c})]$$

$$\text{use } \sinh\ \&\ \cosh\ for\ \zeta = -KL$$

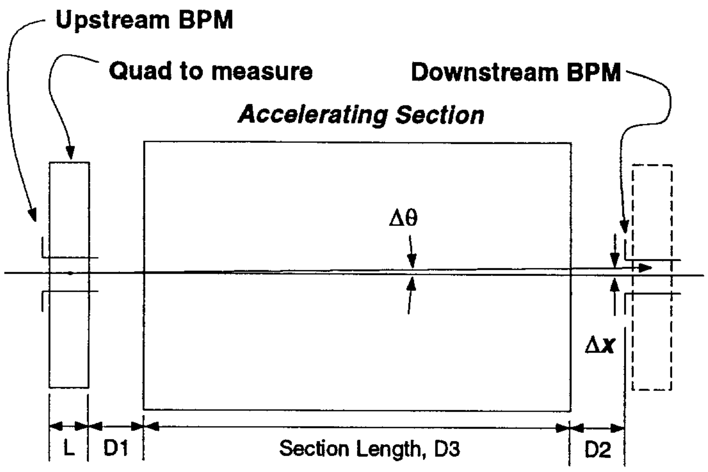
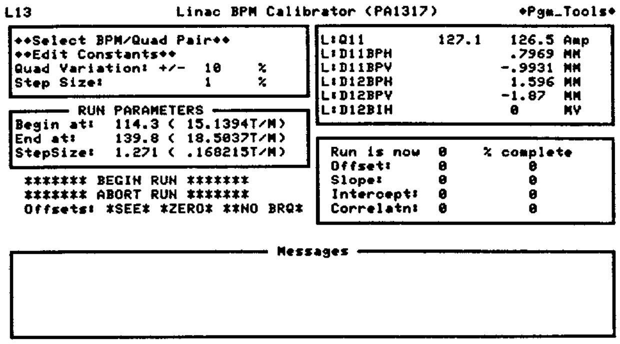


Figure 1, Geometry of the BPM calibration measurement



```
L13                Linac BPM Calibrator (PA1317)                 •Pgm_Tools•

••Select BPM/Quad Pair••              L:Q11          127.1    126.5 Amp
••Edit Constants••                    L:D11BPH                 .7969 MM
Quad Variation: +/-   10    %         L:D11BPV                -.9931 MM
Step Size:            1     %         L:D12BPH                 1.596 MM
                                      L:D12BPV                -1.87  MM
────── RUN PARAMETERS ──────          L:D12BIH                 0     MV
Begin at:   114.3 ( 15.1394T/M)
End at:     139.8 ( 18.5037T/M)
StepSize:   1.271 ( .168215T/M)        Run is now  0     % complete
                                       Offset:     0          0
 ******* BEGIN RUN *******             Slope:      0          0
 ******* ABORT RUN *******             Intercept:  0          0
 Offsets: *SEE* *ZERO* **NO BRQ*       Correlatn:  0          0

──────────────────────────── Messages ────────────────────────────
```

Figure 2, Startup TV screen

If the matrices for a thin lens are used, then we get:

$$x_{final} = \pm KDLx_{init} + x_{init} + Dx'_{init}$$

Differentiating with respect to the quad gradient gives the change in the position at the downstream BPM with respect to the change in the quad gradient:

$$\delta x_{final} = \pm DLx_{init}\,\delta K$$

So the change in the final displacement is directly proportional to the value of the displacement in the quad. Considering that the velocity can change during that drift and reinserting the x' dependance due to a not-so-thin quad, the following relation is obtained:

$$\delta x_{final} = \pm Lx_{init}\left(D_1 + D_2\frac{\beta_{in}}{\beta_{out}} + D_3\frac{2\beta_{in}}{(\beta_{in} + \beta_{out})} + \frac{1}{2}LDx'_{init}\right)\delta K$$

Therefore, if the quad gradient is systematically changed and the change in the position of the beam is measured at the next BPM, then the offset of the beam in the quad can be directly calculated.

The assumptions made here are:

(1) the *relative* beam displacements measured by the BPMs are accurate;

(2) the conversion from amps to magnetic field in the quad is well known;

(3) the distances are well known;

(4) the angle of the beam at the quad is small;

(5) a thin-lens approximation is adequate;

(6) the change in the trajectory due to rf effects in the accelerating module is small and

(7) the momentum is known.

Assumptions 1, 2 and 3 are (*really!*) well known. 4 and 5 enter into the equations similarly and would contribute up to about 15% in the offset. For example, for $D_1+D_2+D_3$ = 2 meters, x_{init}=1mm and x'_{init}=1 milliradian, the x' term contributes about 8% to the observed offset at the downstream BPM and the fact that the quad is not paper-thin contributes about 5%. This makes the difference of measuring an offset of 0.87 mm, rather than 1.00 mm--I consider this acceptable.

III. Using the Program

Armed with this theory, the application program PA1317 has been written. It sits on page L13. The major complication in this program is that not enough BPM-RF modules were constructed to read out all of the BPM channels, but the program ultimately requires information from each BPM.

A run consists of systematically changing a quad from -10% to +10% in 1% steps and observing the change in the position at the downstream BPM. When the program starts, a screen like the one shown in Figure 2 is presented. The only interrupts that should be necessary are "`**Select BPM/Quad Pair**`" and "`* BEGIN RUN *`". The "`Select`" field makes a pull-down menu for selecting a quad. This is the quad on which the measurement is made. The program selects the BPMs to read based on the quad choice. Since all the BPMs do not read back in the control system, it will be necessary to change BPM cables in the Linac Diagnostics Room. All BPM channels are cabled, but only about two-thirds are readout by default. The BPMs which the program uses and the places where there are no readbacks are listed in Table 1.

Table 1, Quad-BPM Translation

Quad	Inside this quad		Downst'm from this quad	
	Horiz BPM	Vert BPM	Horiz BPM	Vert BPM
L:Q01	L:BPH5OT	L:BPV5OT	L:D01BPH	L:D01BPV
L:Q02	L:D01BPH	L:D01BPV	L:D02BPH	L:D02BPV
L:Q03	L:D02BPH	L:D02BPV	L:D03BPH	L:D03BPV
L:Q04	L:D03BPH	L:D03BPV	L:D11BPH	L:D11BPV
L:Q11	L:D11BPH	L:D11BPV	L:D12BPH	L:D12BPV
L:Q12	L:D12BPH	L:D12BPV	L:D13BPH	L:D13BPV
L:Q13	L:D13BPH	L:D13BPV	*(1)*	*(1)*
L:Q14	*(1)*	*(1)*	L:D21BPH	*(3)*
L:Q21	L:D21BPH	*(3)*	*(2)*	L:D22BPV
L:Q22	*(2)*	L:D22BPV	L:D23BPH	*(3)*
L:Q23	L:D23BPH	*(3)*	*(1)*	*(1)*
L:Q24	*(1)*	*(1)*	L:D31BPH	*(3)*
L:Q31	L:D31BPH	*(3)*	*(2)*	L:D32BPV
L:Q32	*(2)*	L:D32BPV	L:D33BPH	*(3)*
L:Q33	L:D33BPH	*(3)*	*(2)*	L:D34BPV
L:Q34	*(2)*	L:D34BPV	L:D41BPH	*(3)*
L:Q41	L:D41BPH	*(3)*	*(2)*	L:D42BPV
L:Q42	*(2)*	L:D42BPV	L:D43BPH	*(3)*
L:Q43	L:D43BPH	*(3)*	*(2)*	L:D44BPV
L:Q44	*(2)*	L:D44BPV	L:D51BPH	*(3)*
L:Q51	L:D51BPH	*(3)*	*(2)*	L:D52BPV
L:Q52	*(2)*	L:D52BPV	L:D53BPH	*(3)*
L:Q53	L:D53BPH	*(3)*	*(2)*	L:D54BPV
L:Q54	*(2)*	L:D54BPV	L:D61BPH	*(3)*
L:Q61	L:D61BPH	*(3)*	*(2)*	L:D62BPV
L:Q62	*(2)*	L:D62BPV	L:D63BPH	*(3)*
L:Q63	L:D63BPH	*(3)*	*(2)*	L:D64BPV
L:Q64	*(2)*	L:D64BPV	L:D71BPH	*(3)*
L:Q71	L:D71BPH	*(3)*	L:D72BPH	L:D72BPV
L:Q72	L:D72BPH	L:D72BPV	L:D73BPH	L:D73BPV
L:Q73	L:D73BPH	L:D73BPV	L:D74BPH	L:D74BPV
L:Q74	L:D74BPH	L:D74BPV	*(1)*	*(1)*
Notes:	(1) BPM does not exist (2) Horiz readback for this BPM does not exist; use L:D74BPH (3) Vert readback does not exist; use L:D74BPV			

`~/controls/cnsappl/bpmcal/Quads.table`

On those BPM channels with no RF modules, the cables for this BPM should be connected to the RF module for either `L:D74BPH` or `L:D74BPV`--the program will tell you which. Jumper cables might be necessary; just be sure that the two cables are the same length and that the connectors are on tight. The cable marked HL (for Horizontal Left) should be plugged into the top connector of the BPM-RF module and the HR cable should go into the bottom connector. Similarly, VB (for Vertical Bottom) should go into the top and VT should go into the bottom.

The box in the upper-right-hand corner of the TV screen contains the database parameters which the program is using. The first line is, of course, the quad. The next five lines represent the BPMs which contribute to the measurement: Line 2 is the horizontal plane of the BPM inside the quad; line 3 is the vertical plane of that BPM; line 4 is the horizontal plane of the BPM downstream of the quad, line 5 is the vertical plane; line 6 is the BPM intensity readback which the program uses to determine if there is beam available. The device `L:D74BPH` or `L:D74BPV` is substituted (in red) automatically if the BPM channel is not otherwise available.

The run parameters for the quad limits, expressed in percent of the original value, can be changed in the normal way.

Due to losses in the linac, it may be necessary to scale back the rate at which the program requests beam. There is an interrupt for that in the middle of the TV screen which cycles through 15 Hz, 7 Hz, 3 Hz, 1 Hz and no beam request ("`NO BRQ`"). I have found that 3 Hz is about the maximum. It may be necessary to go to `NO BRQ` and use the Linac HP waveform generator to regulate the beam rate. For most quads, this program has minimal effect on booster beam (but keep an eye on it anyway!).

The interrupt "`*Edit Constants*`" may be useful. Mostly, these values are from the surveying results and should not be changed unless they are clearly wrong. The parameters are: quad length, drifts, section length, quad conversion, β_{in}, β_{out}, limits on the BPM plot, BPM threshold, the number of points to average, and the last measured offsets for the downstream BPM. If this program is being used during dedicated linac study time and the acceleration can be turned off, then it should be verified through this menu that the input and output βs are correct.

A normal run would go like this. Select a quad, say, `L:Q11` and remove it from the alarm scan on a parameter page. Interrupt on "`* BEGIN RUN *`" and watch the program change the current for `L:Q11`. Keep an eye on `L:200SCA` to be sure that losses are not too high. When the run has finished, the program will put the quad back to the original value and record the "offsets" information internally. All information should also be recorded separately.

Table 2 shows results from a typical set of runs. It can be verified that the program has correctly recorded the information by interrupting on the "`*SEE*`" field. The "Prog." column in this table is the number which the program calculates as the offset of the beam in the quad; the "BPM" number should be the reading of the BPM calculated by the program during the measurement, in other words, the averaged readback from the BPM with whatever offsets the program has so far subtracted off. The "offset" column is made by subtracting the value in the "prog." column from the value in the "BPM" column. The "Intercept" numbers are also calculated by the program and should be on this list.

Table 2, Typical Results for PA1317

Quad	Setp't	H Offset, measured			V Offset, measured			H Int'cpt	V Int'cpt
		Prog.	BPM	Offset	Prog.	BPM	Offset		
L:Q11	127.1 A	0.383	0.992	0.611	-0.326	-0.833	-0.507	3.111	-0.4657
L:Q12	156.2	0.169	1.662	1.493	-0.376	-1.705	-1.329	-1.131	-2.215
L:Q13									
L:Q14									

`~/controls/cnsappl/bpmcal/Example.table`

IV. Analyzing the Results

The progressing results can be checked for consistency by comparing the "offset" number predicted by the program with the reading from the BPM being measured (the one in the quad). Absolute differences of 2 mm or more are suspect. Usually, we should get about 1 mm or less for the offsets. In Table 2, both planes of the BPM `L:D12BP*` indicate that the center of the quad is more that 1 mm from what the BPM says is zero.

When all of the quads have been measured once, it should then be valid to pay attention to the "intercept" value calculated by the program. This number is the best gauge on how much the angle of the beam and the thickness of the quad are contributing to the results. Keep an eye on this number as you go and highlight the big ones. 5 mm is big. It will take some experience to interpret these numbers meaningfully.

The program will remember the offset numbers which are measured so that as the measurements are made, this offset is internally applied to that BPM's readback when it uses it again. Therefore, I would like to run through all the BPMs at least twice.